The work described in this report has been carried out under the contract agreement with EOARD:

Contract Title: Active Vibration Reduction for Avionic Equipment

Date: 1st July 1992

ACTIVE DAMPING

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1992	Final Report

4. TITLE AND SUBTITLE

Active Damping

5. FUNDING NUMBERS

F6170892W0079

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC-92-4026

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

Feedback has been used to control the vibration of dynamic structures for a number of years. The choice of sensor/actuator has always been the major challenge in feedback control. Piezoelectric materials with their small size and high sensitivity to very small displacement and forces offer a good and practical alternative to traditional magnetic or hydraulic sensor/actuators. The inverse piezoelectric effect is a property of piezoelectric materials which can be fully exploited when one component is used as both the sensor and the actuator. The initial aim of this study is to investigate how piezoceramics perform in a feedback control configuration. Subsequently the aim will be to apply the active damping concepts to plate and beam.

14. SUBJECT TERMS

15. NUMBER OF PAGES

25

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Progress Report No. 1, October 1992

VIBRATION CONTROL USING PIEZOELECTRIC MATERIALS

ACTIVE DAMPING

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1 - Introduction :

Feedback has been used to control the vibration of dynamic structures for a number of years. The choice of sensor/actuator has always been the major challenge in feedback control. Piezoelectric materials with their small size and high sensitivity to very small displacement and forces offer a good and practical alternative to traditional magnetic or hydraulic sensor/actuators. The inverse piezoelectric effect is a property of piezoelectric materials which can be fully exploited when one component is to be used

as both the sensor and the actuator.

Many advances have been made in the use of piezoelectric ceramics and piezoelectric polymers in vibration control problems. Theoretically models have been developed to predict the behaviour of an actively controlled structure consisting of alternate layers of piezoelectric sensors and actuators connected to the structure. These type of structures are better known as smart structures.

In the area of smart structures the concept of active damping has received considerable attention in the past few years. The basic idea of active damping is that piezoelectric materials can be used to induce extra damping in a structure, hence reducing the vibration levels in various modes of vibration of a structure. The extra damping can be generated in a structure by a number of methods. One method is to apply a force to the structure which is 90 degrees out of phase to the motion of the structure without using any passive damping elements. Another technique is to enhance the damping of a passive element in the structure by active means. This can be done very effectively when constrained layer damping is used. The constraining layer is bonded to the structure using a viscoelastic material which acts as a passive damping element. The constraining layer induces shear in the damping material hence improving the damping properties of the structure. One way of inducing even further shear in the damping material is to actively control the motion of the constraining layer. There are two ways of achieving this. One is to use a piezoelectric polymer as the constraining layer and control its motion by applying the appropriate voltage across it. A report prepared for the U.S. Air Force Astronautics Laboratory in August 1988 written by The Charles Stark Draper Laboratory, Inc. report number AFAL-TR-88-038 examines this technique in detail.

The second technique is to use piezoelectric materials in addition to a constraining layer.

This is the approach used in the present study.

The initial aim of the study is to investigate how piezoceramics perform in a feedback control configuration. Subsequently the aim will be to apply the active damping concepts to plate and beam.

2 - Experimental Procedures :

Three sets of experiments have been carried out up to the present time.The first two experiments produced qualitative results and paved the way for the third experiment to be carried out from which quantitative results were obtained.

2.1 - Experiment No. 1 :- ACTIVE CONTROL USING BENDING FORCES :

Fig. 1 shows the apparatus used in experiment 1 and fig. 2 the details of the beam used. The experimental procedure was simply to shake the beam at the natural frequency of the first mode of vibration and vary the amplifier gain in the feedback loop which would in turn vary the voltage applied to the piezoceramic and then to observe the effect on the amplitude of vibration of the beam.

The piezoceramic used was a Philips PXE5 parallel bimorph, catalogue number 432202014600 which has a tip deflection of 300 micrometer at 300 volts peak to peak. The objectives of the experiment were to find ;

a) What type of bonding agent is suitable for vibration control applications ?

The bonding agent used was Araldite Epoxy resin with a setting time of 48 hours. This

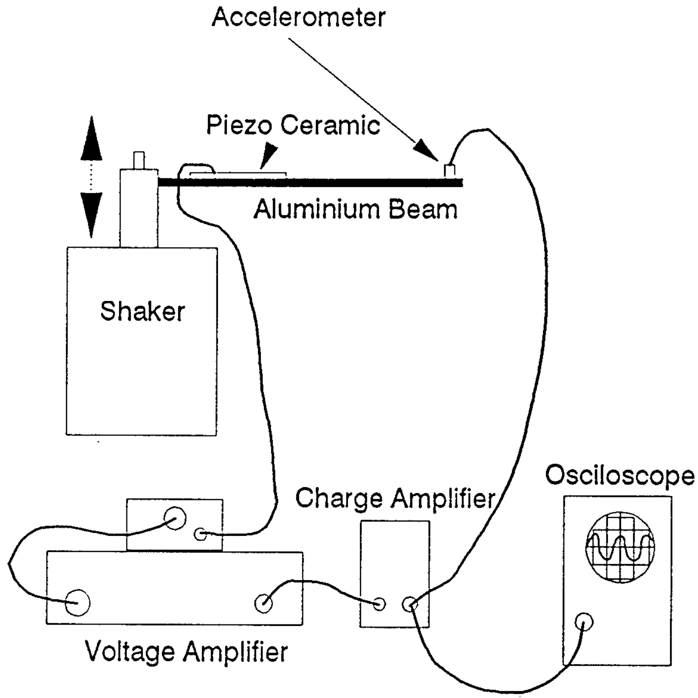

Fig. 1 - Experimental Set up 1

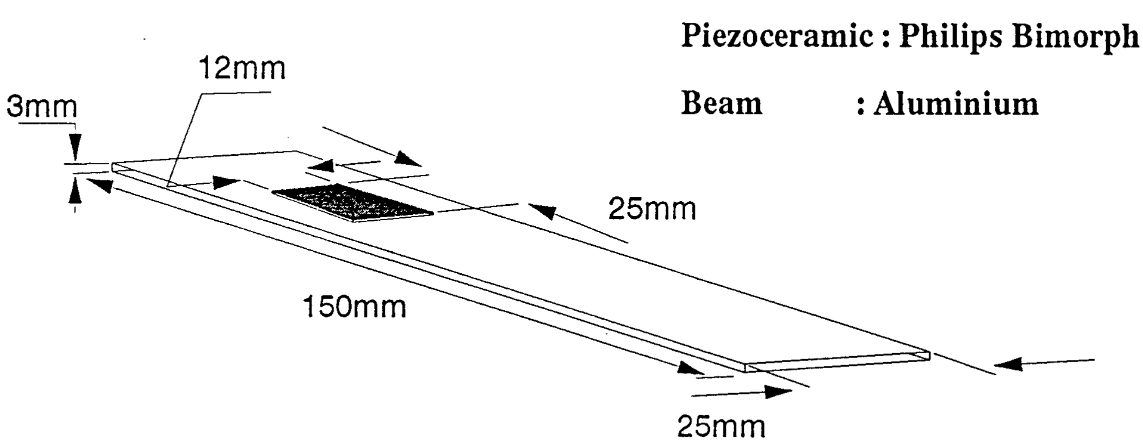

Fig. 2 - Beam Used in Experiment 1

is a rigid bonding material and proved to be effective in the subsequent tests.

b) What is a suitable feedback configuration ?

The feedback configuration was as follows: the sensor signal was used as the input to an inverting amplifier. This was input to a variable gain voltage amplifier and was then fed back into the piezoceramic. Therefore the feedback signal is 180 degrees out of phase with the sensor signal.

c) How could the voltage required to drive the piezoceramic be produced ?

The voltage (in the order of 500 volts peak to peak) was produced by a conventional transformer with a secondary to primary ratio of 50:1. The input voltage was limited to 10 volts peak to peak.

d) What is the best signal to feedback ?

There was a choice of sensor signal to generate the feedback voltage. These were displacement, velocity or acceleration. All were tried and acceleration produced the best result with a conventional accelerometer as the sensor. When a strip of piezoelectric polymer was used instead of the accelerometer the displacement signal produced similar results.

e) What is the best type of sensor to be used ?

The type of sensor is determined by the application. An accelerometer placed at the tip of the beam is the most obvious solution for the test set-up. In real applications this may not be the best solution particularly for plates and beam structures in which distributed

sensors are required. A strip of PVDF material glued to the structure is one other alternative which was tried. This method has advantages in terms of compactness and ease of attachment. However the positioning of the strip on the structure proved to be critical and requires further investigation.

f) Where are the best locations for the Piezoceramic and the sensors ?

The best location for the piezoceramic was near the base of the beam where maximum curvature occurs. The best position for the accelerometer is at the tip where maximum signal level is detected. If a PVDF strip is used as the sensor the best position for it is directly opposite the piezoceramic (on the opposite side of the beam).

g) By what factor could the vibration levels be suppressed ?

With a maximum voltage of 500 volts peak to peak applied to the piezoceramic, the vibration levels of the beam were reduced to approximately %15 of the vibration levels of the uncontrolled beam.

2.2 - Experiment No. 2 :- ACTIVE CONTROL AND ACTIVE DAMPING OF THE FIRST MODE OF VIBRATION :

The apparatus used in this experiment is shown in fig. 3 in which a sine sweep and a random signal were applied to the shaker and the acceleration at the tip of the beam was measured. The piezoceramic used in this experiment was a Philips PXE5 single layer plate, catalogue number 433202013580. The objectives of the experiment were to answer the following questions;

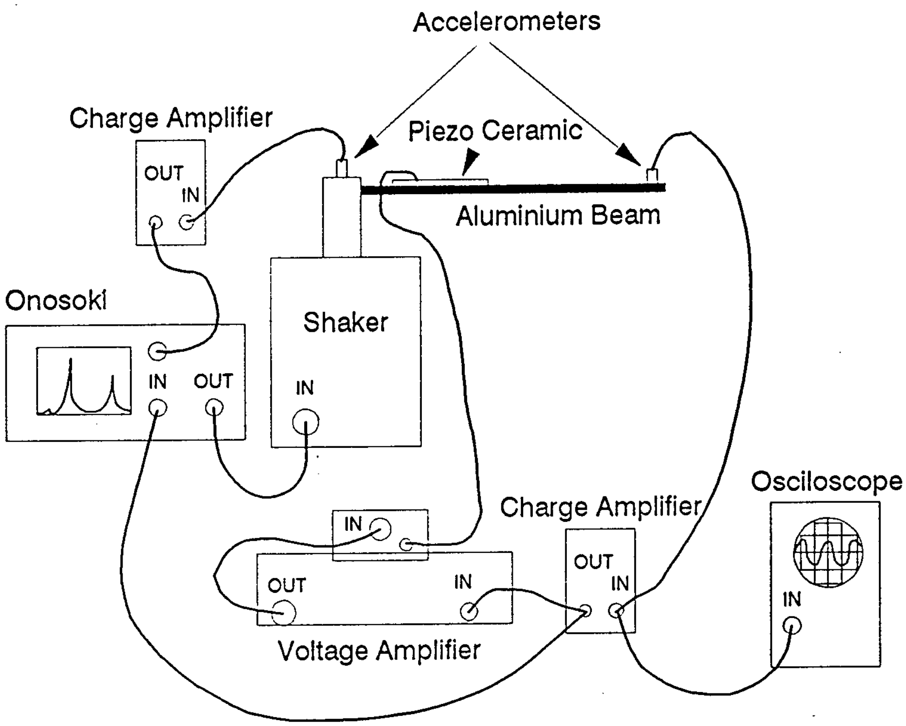

Fig. 3 - Experimental Set up

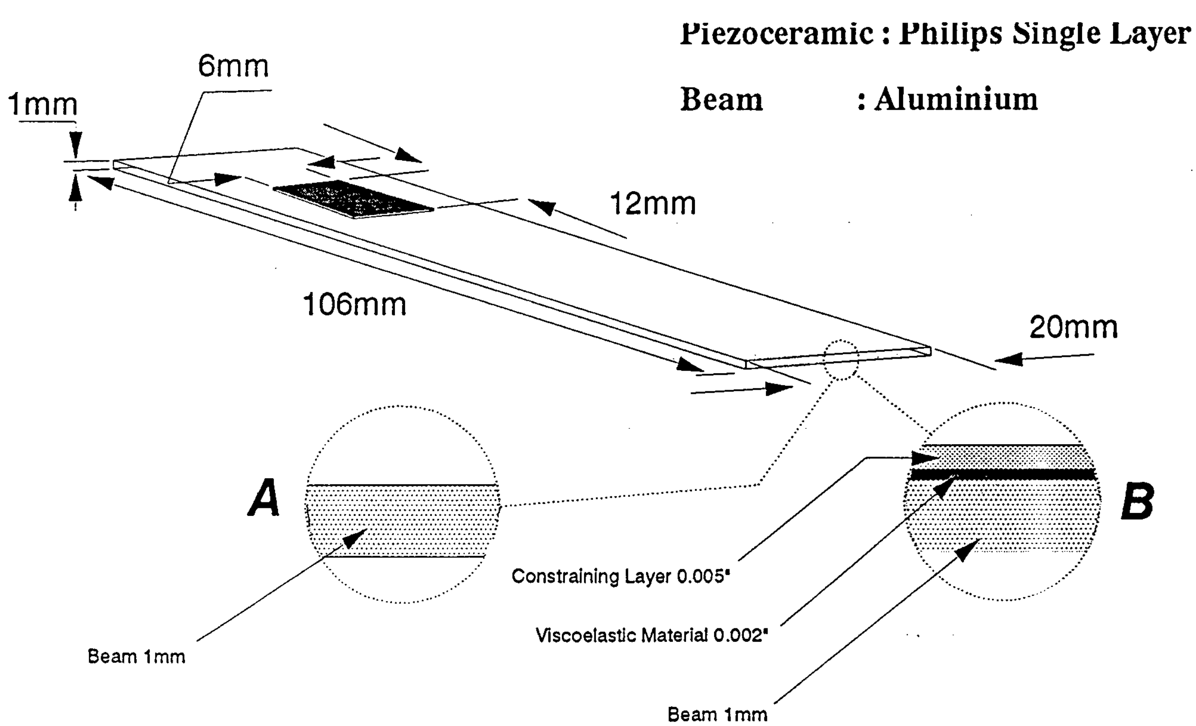

Fig. 4 - Beams Used in Experiment 2

a) How do single layer piezoceramics compare to bimorph piezoceramics in terms of effectiveness in vibration suppression ?

The fundamental difference between single layer piezoceramic plates and piezoceramic bimorphs is the type of force that they apply to the structure to which they are bonded. Bimorphs apply a bending force to the structure and are particularly useful when the required deflection is large and the forces involved are small. Single layer ceramics apply a shear strain to the surface of the structure creating a moment about the neutral axis which can counteract the vibration moments. Single layer ceramics can apply larger forces to a structure and perform well when the required deflections are small. For the concept of active constrained layer damping, single layer ceramics should in principle produce better results because they can induce more shear in the viscoelastic damping material.

In this experiment a direct comparison was not possible due to different size of structures and ceramics. However in terms of driving circuitry and vibration suppression the two types of ceramics produced very similar results.

b) How do faster setting bonding elements compare to Araldite resin ?

In order to compare bonding agents two identical beams, of the type shown in fig. 4a, were used with identical piezoceramic plates bonded to both. The bonding agent used on the first beam was Araldite Epoxy resin with a setting time of 48 hours and the second bonding agent was rapid adhesive X60 strain gauge glue with a setting time of 15 mins. It was found there was no appreciable difference in terms of vibration suppression between the two beams. The faster setting glue is more brittle however and in applications where large forces are involved this may prove to be a disadvantage.

c) Does the concept of active damping work with piezoceramic elements and constraining layers ?

The two beams shown in fig. 4a and 4b were used to investigate the active damping concepts. The first beam is an aluminium beam with a single layer piezoceramic bonded to it. The second beam is identical except for the fact that it has a constraining layer and a viscoelastic layer, which form a damping layer, between the piezoceramic and the beam. The damping layer is called SOUNDFOIL (manufactured by SOUNDCOAT Co). and consists of aluminium foil of thickness 0.005" coated with modified copolymer of thickness 0.002" which can directly stick to the structure. The idea is to examine how the constraining layer changes the vibration levels in the beam. This experiment was designed to focus on the first mode of vibration of the beams only. The voltage applied to the piezoceramics was limited to 300 volts peak to peak. The results are shown in figs. 5 to 7. Fig. 5 shows the improvement in the damping of the first beam using simple feedback. Fig. 6 shows the same result for the second beam with constrained layer damping material added. From both figures it is apparent that active feedback control improves the damping of both beams. However the purpose here is to compare active and passive damping and this comparison can be made using fig. 7. As can be seen, the sample which utilises both the constraining layer and the piezoceramic element produces a lower resonant peak than the sample with a piezoceramic plate and no constraining layer. Note that the tests carried out on both beams were identical and the same voltages were applied to the piezoceramics on each beam.

The conclusion drawn from this experiment was that the particular approach used here to create active damping does improve the damping in the system.

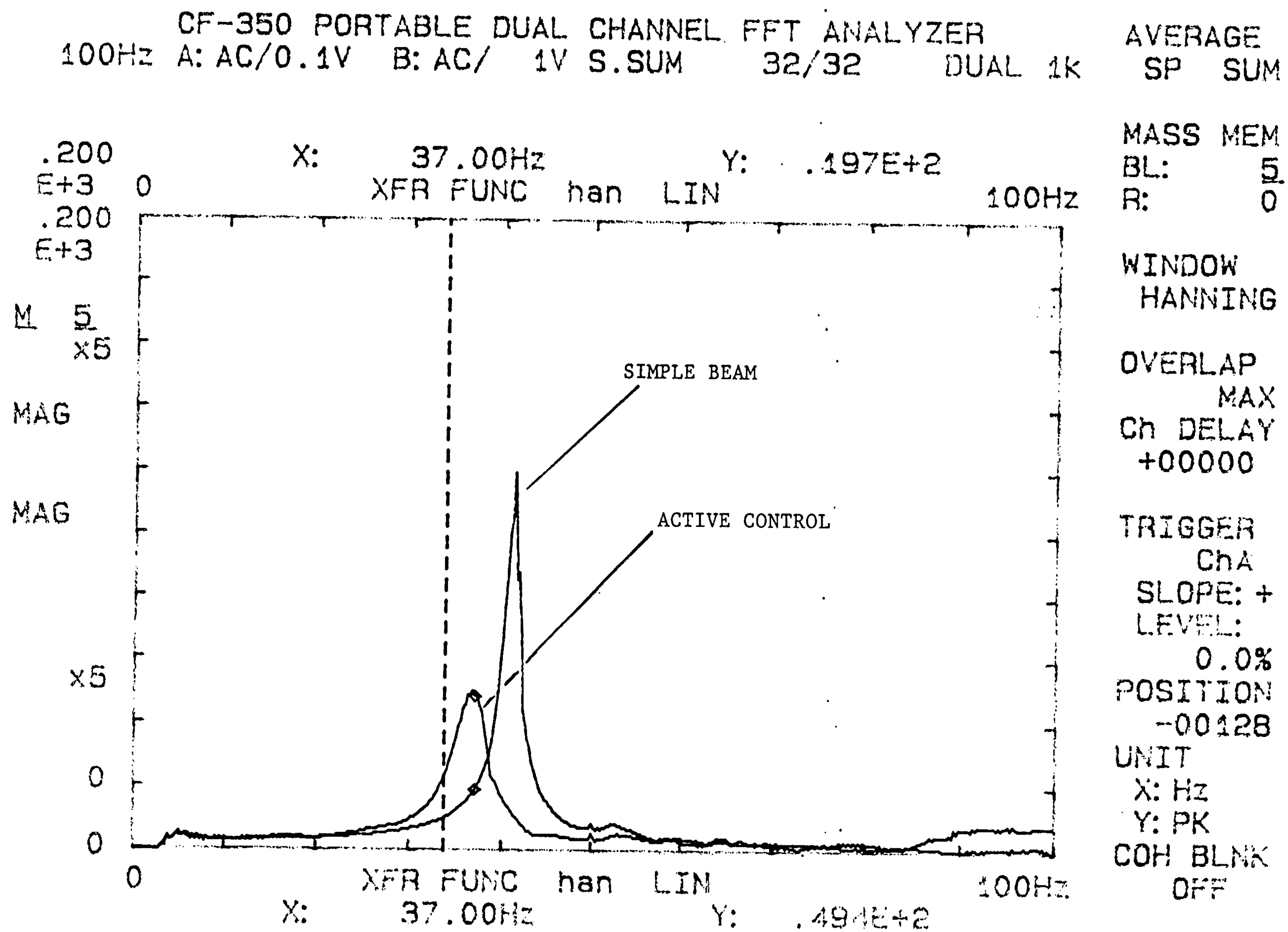

Fig. 5 - Simple Beam With and Without Feedback

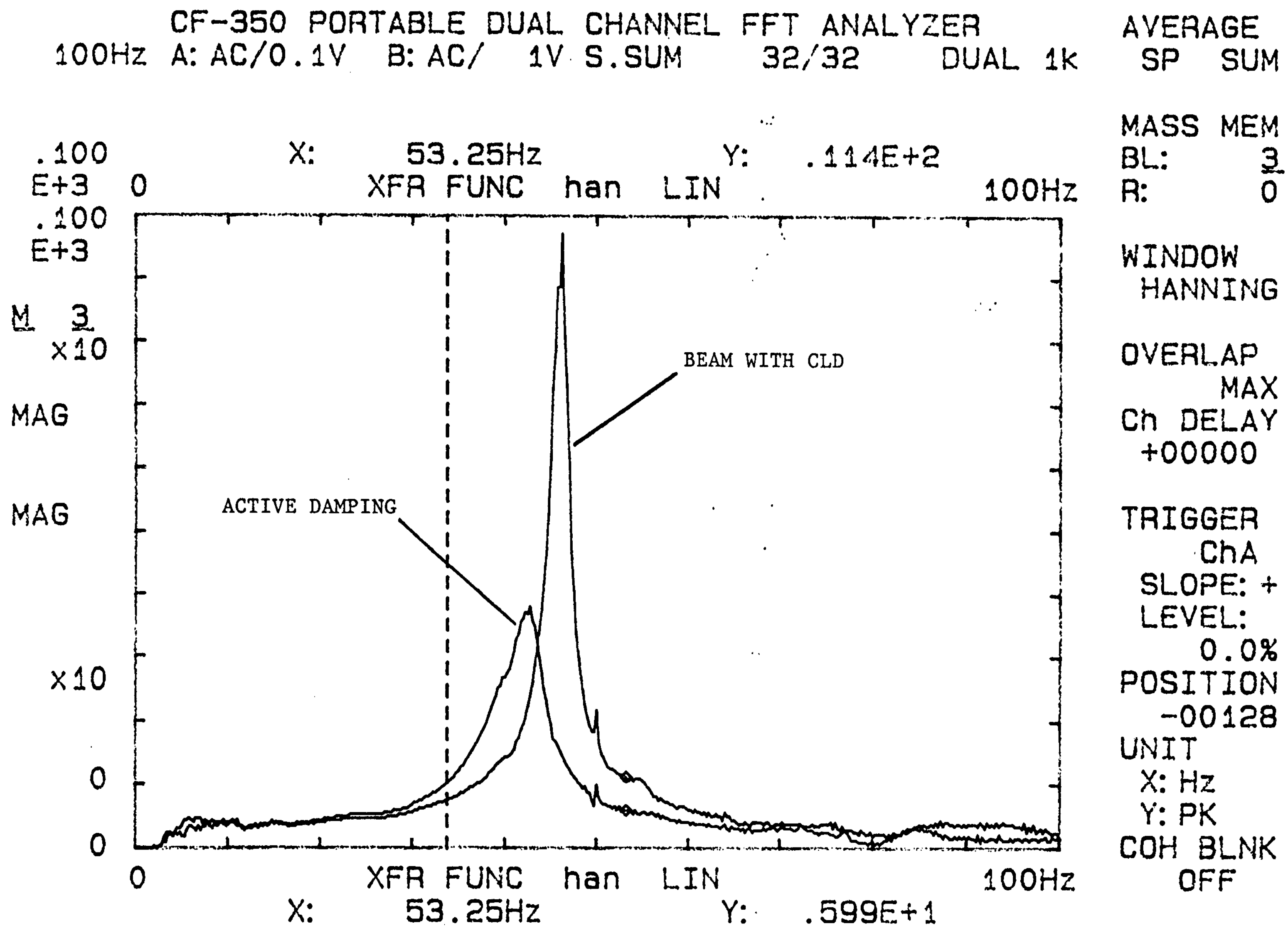

Fig. 6 - Beam with Constrained Layer Damping With and Without Feedback

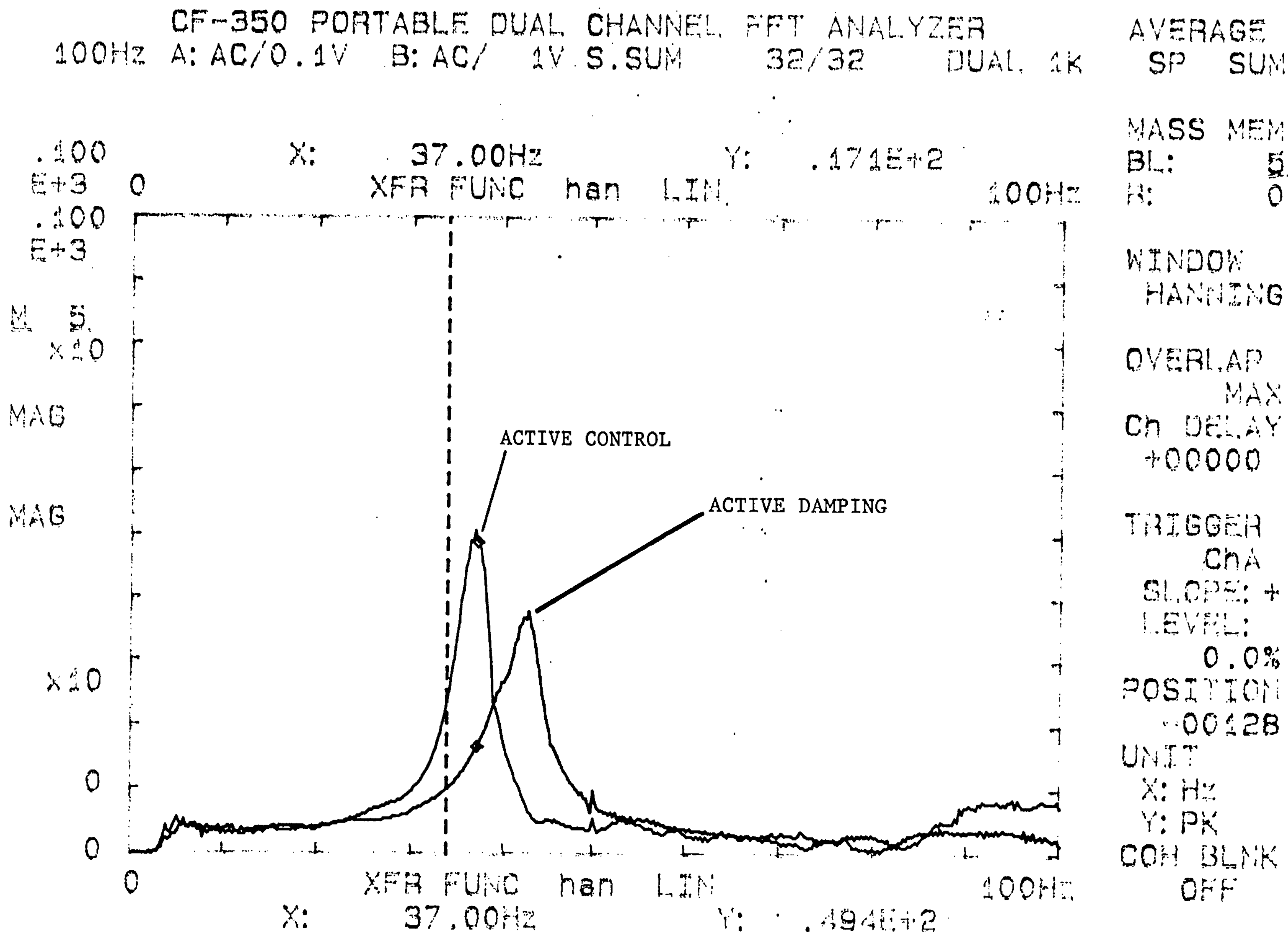

Fig. 7 - Active Control of Simple Beam vs Active Damping of Beam with CLD

2.3 - Experiment No. 3 :- ACTIVE CONTROL AND ACTIVE DAMPING OF THE FIRST AND SECOND MODES OF VIBRATION :

The set up of this experiment was identical to that of fig. 3, the beam dimensions are shown in fig. 8. The procedure was to apply periodic random and sine sweep signals to the beams and measure the response at the tip of the beams as the feedback gain is varied. The objectives of this experiment were to find ;

a) Whether and how are the higher modes of vibration affected by active damping ?

In order to investigate the effect of active damping on both the first and the second modes of vibration a band limited random signal in the frequency band of 0-1000 Hz was applied to the shaker. The beams were designed to have their first mode at 110 Hz and their second mode at 625 Hz. The frequency response function between the tip of the beams and the shaker were obtained for various values of the feedback gain. This was done on two beams, one with constrained layer damping and the other without. The results are shown in figs. 9-11. The effect of feedback on a beam without constrained layer damping is shown in fig. 9. It can be seen that increasing the feedback gain reduces the vibration levels at both modes. However the reduction is much more significant in the first mode than the second mode. Fig. 10 shows the results for a beam with constrained layer damping. Note that the vibration levels are lower even without feedback. When feedback is used the situation improves further as shown in fig. 11 which summarizes the results of the two tests. There are four cases shown in fig. 11, a beam with no feedback and no added damping (simple beam), a beam with no feedback and added constrained layer damping (CLD only), a beam with feedback and no

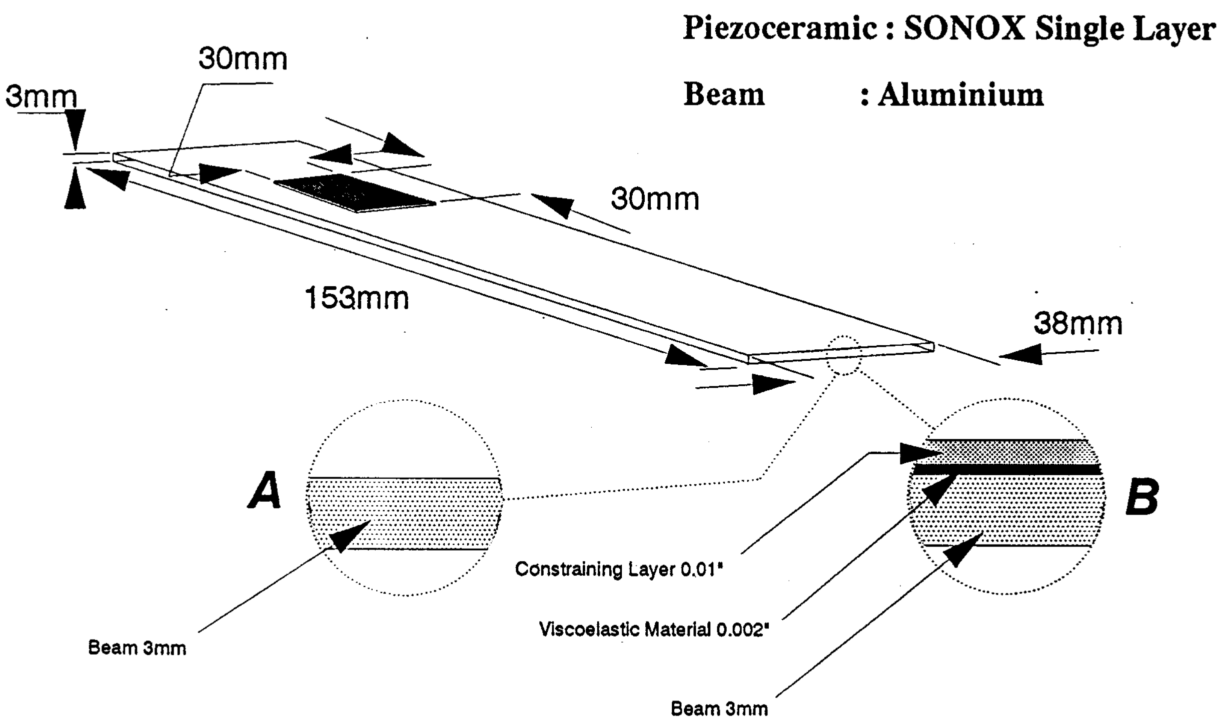

Fig. 8 - Beams Used in Experiment 3

constrained layer damping (active control), and finally a beam with constrained layer damping and feedback control (active damping).

The simple beam has the highest peaks at both modes of vibration. The damping ratio, ζ, for the simple beam are 0.0039 in the first mode and 0.0028 in the second mode. Important results are obtained when both modes of vibration are examined closely for each of the four cases mentioned above. Considering the beam with CLD only it can be seen that the second mode is attenuated significantly more than the first mode. This is not surprising because passive damping elements tend to perform better at high frequencies. The damping ratio is 0.0088 in the first mode and 0.0157 in the second mode. On the other hand, the beam with active control has a much lower vibration level in the first mode than in the second mode. Active control increases the damping in the first mode to 0.059 (fifteen times the simple beam), and to 0.0064 (over twice simple beam). Finally the beam with active damping combines the benefits of active control at the first mode and passive damping at the second mode and reduces the vibration levels even further and produces the lowest levels at both modes of vibration. The damping ratio in the first mode increases to 0.0788, almost 20 times the damping factor of the simple beam and ten times that of the beam with CLD, and in the second mode the damping factor increases to 0.0202, a ten times improvement on the simple beam and 3 times improvement over the beam with active control (See table 1).

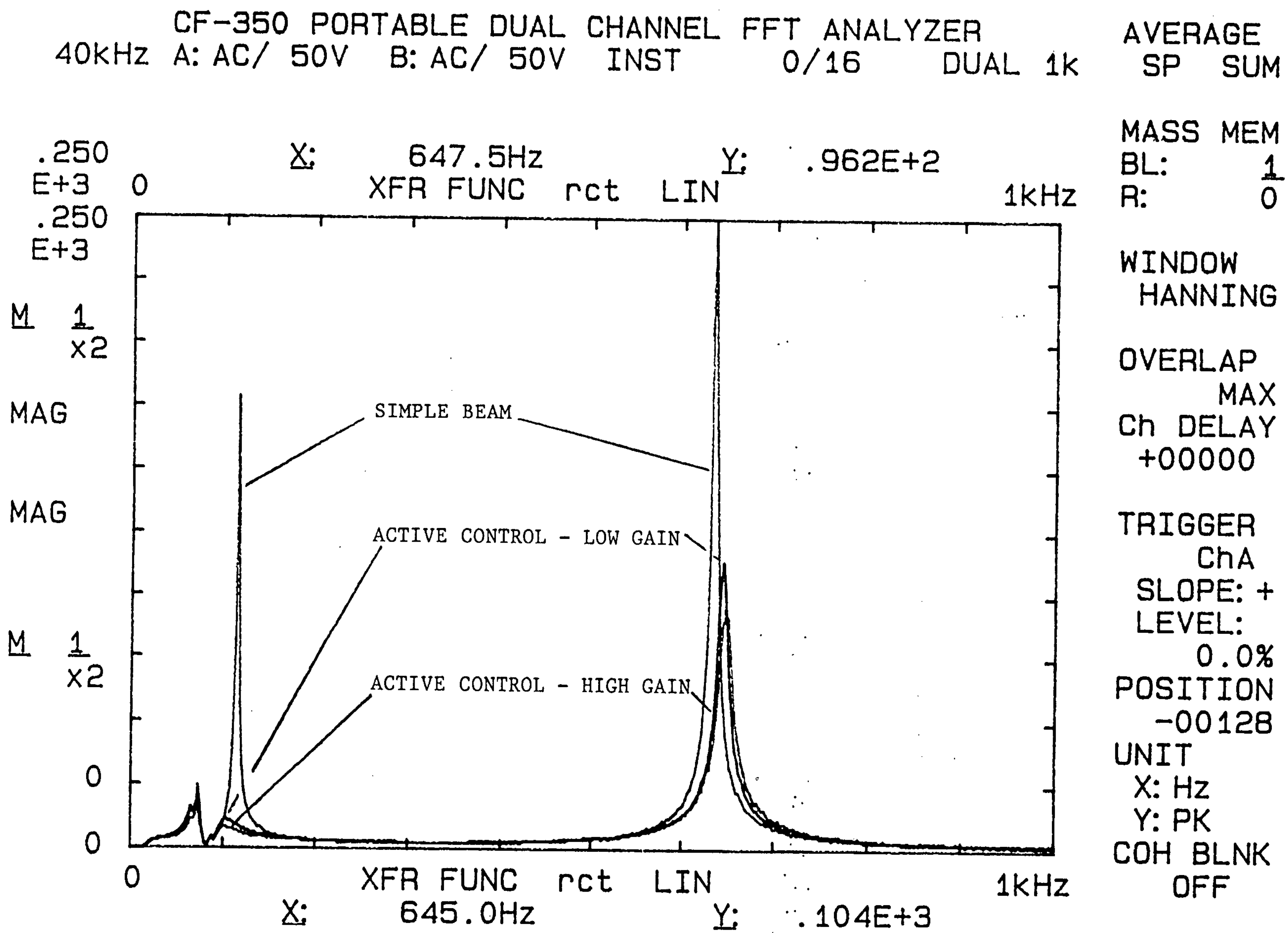

Fig. 9 - Simple Beam With Varying Degrees of Feedback

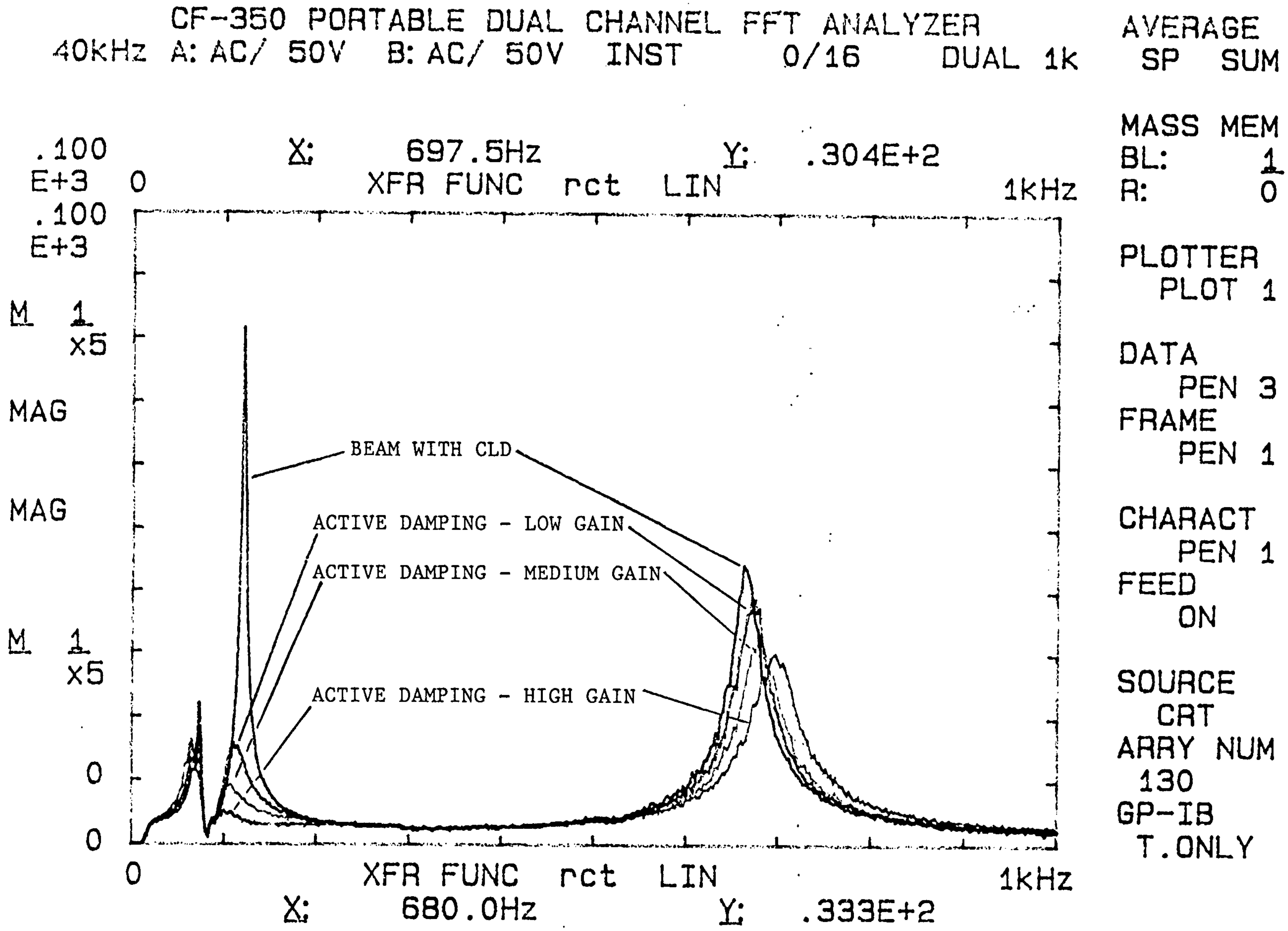

Fig. 10 - Beam with CLD and Varying Feedback Gain

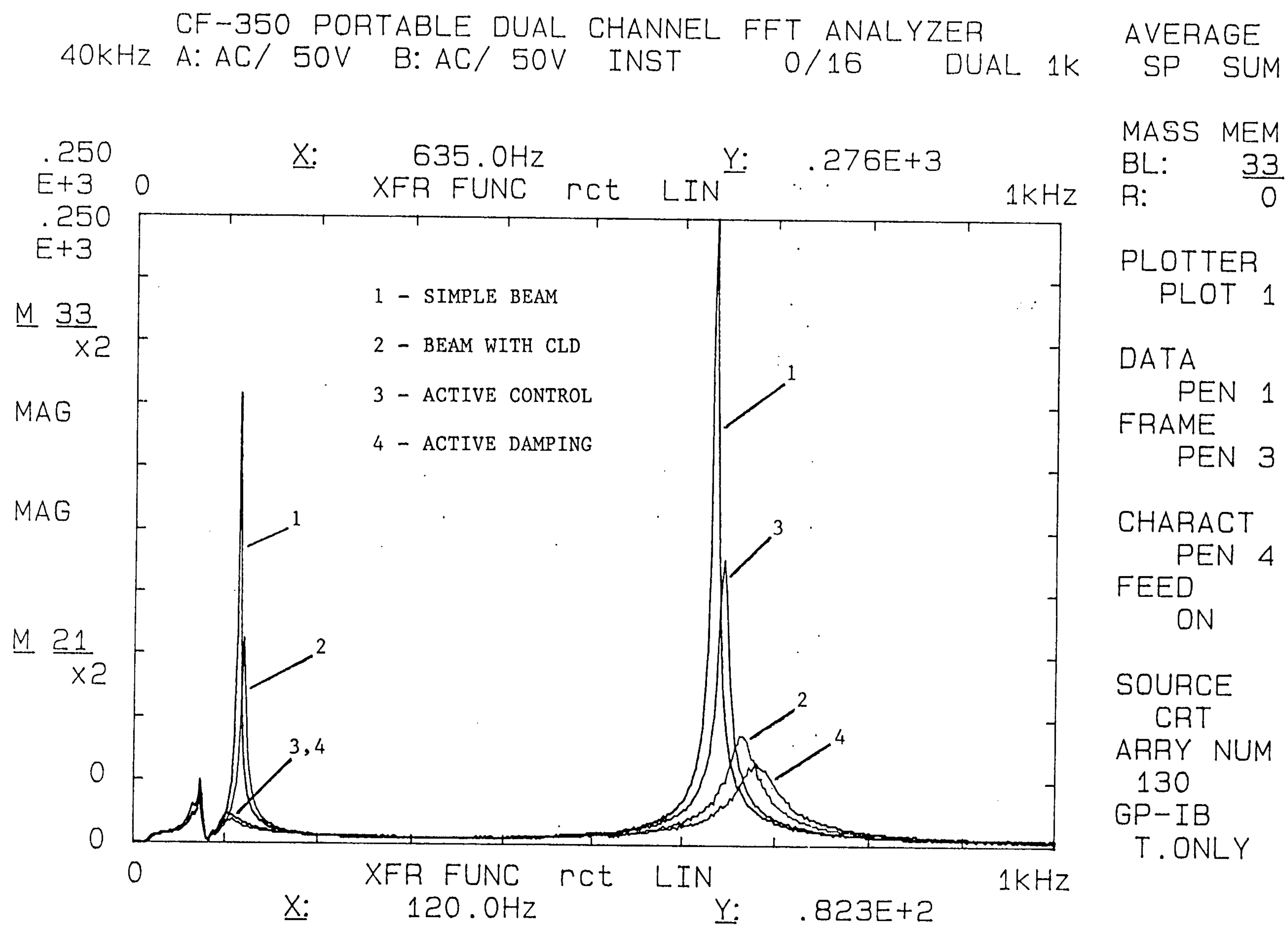

Fig. 11 - Comparison of Passive Damping, Active Control and Active Damping

Beam Type	Damping Ratio	
	First Mode	Second Mode
Simple Beam	0.0039	0.0028
Beam with CLD	0.0088	0.0157
Active Control	0.0590	0.0064
Active Damping	0.0788	0.0202

Table 1

Comparison of the Damping Ratios at the First Two Modes of Vibration

b) What is the relationship between the feedback voltage and the effectiveness of the piezoceramic ?

The effectiveness of the piezoceramic is measured by how much the vibration can be suppressed in the structure. Ideally this should be a linear relationship, although in practice it was found that the higher the feedback voltage the more effective the ceramic suppresses the vibrations up to a certain voltage. This is either the voltage at which the amplifier saturates or the voltage at which the voltage generated across the ceramic counteracts the increase in the voltage applied to the ceramic. It is important to bear in mind when working with piezoceramics that the actual voltage across the ceramic is the difference between the applied voltage and the voltage generated in the ceramic as a result of the motion of the beam.

c) Can the damping be changed without affecting the stiffness of the system ?

Figs. 9 to 11 show that the introduction of feedback in either of the beams not only changes the damping in the beams but also affects the natural frequencies and hence the stiffness of the beams. In order to generate active damping in the beams it is preferable to maintain the same stiffness and increase the damping only because this will ensure that all the energy applied to the feedback system is dissipated as extra shear in the viscoelastic layer which in turn means there is direct control on the damping. To examine the feasibility of this idea and gain an understanding of the reasons behind the change in the stiffness of the beams a simple computer model was developed for the purpose of simulation. The Frequency Response Function (FRF) of this model is shown in fig. 12. The model has four poles and two zeros and the FRF is plotted for a negative feedback configuration. Comparison of figs. 11 and 12 shows good agreement in principle as far the change in the stiffness is concerned between the model and the actual system. Considering the graph with the highest change in stiffness at the second mode in fig. 12 (feedback gain of 0.5), it is possible to decrease the stiffness towards its original value by adding a simple lag element to the feedback loop. In practice a phase lag oscillator is used. The effect is shown in fig. 13. This idea is currently being tested on the actual beams.

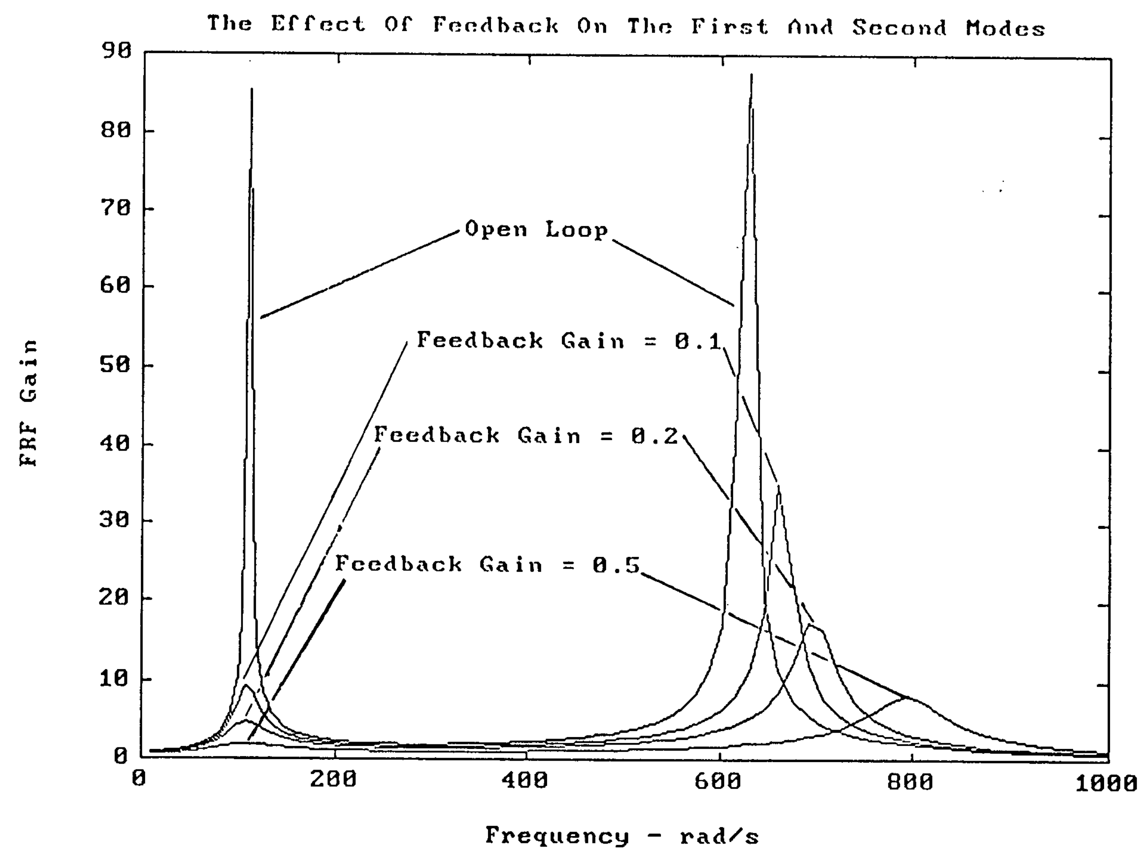

Fig. 12 - Simplified Model of the Beam with Various Feedback Gains

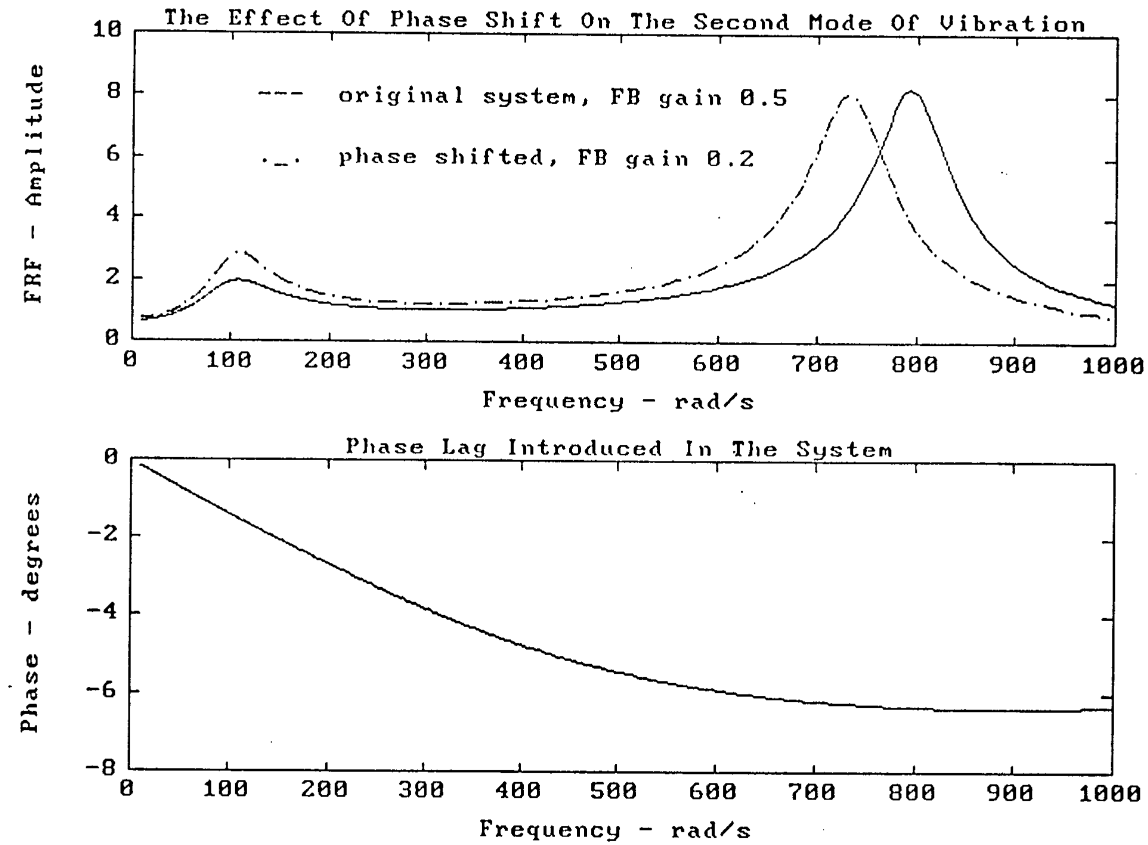

Fig. 13 - Reducing the Stiffness of an Actively Damped Beam Using Phase Lag

d) How do the results from a transient test compare to results of the frequency response tests ?

To verify the results obtained from frequency response tests an independent set of tests were carried out using transient tests. Transient responses were obtained for a simple beam, a beam with CLD only, a beam with active control and finally an actively damped beam. The results in the form of impulse responses are shown in fig. 14. The settling time of the beam reduces considerably as a result of active control and active damping. For example the settling time of the simple beam is about 1 second compared to the settling time of the actively damped system of 0.1 second. The difference between active control and active damping is not noticeable because in the transient tests primrily exite the first mode.

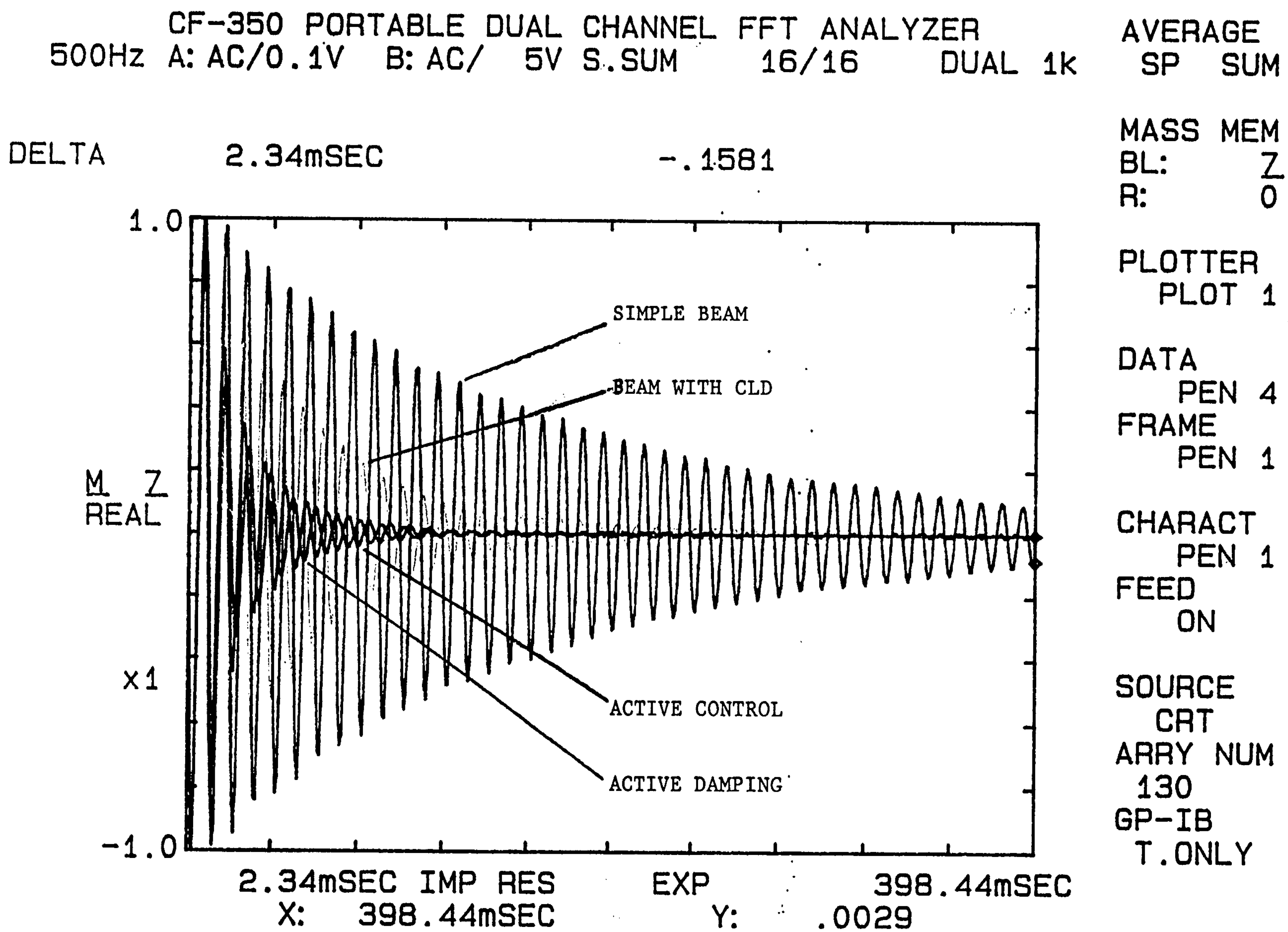

Fig. 14 - Impulse Response, Passive Damping, Active Control & Active Damping

3 - Conclusions :

1 - It has been shown that active damping using an actively controlled constraining layer produces superior results to passive damping and to active control when applied to vibration of beams.

2 - The results obtained from frequency response tests and transient tests indicate a considerable improvement in the damping ratio of beams in the first and second modes of vibration.

3 - Further work is required to extend the applications to plate structures where torsion is present as well as bending.

4 - In order to investigate various control laws further work is required to develop an accurate mathematical model of actively damped structures.